

SEASONAL SNOW EXTENT AND SNOW MASS IN SOUTH AMERICA USING SSMI PASSIVE MICROWAVE DATA¹

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Abstract: Seasonal snow cover in primarily non-mountainous areas of South America was examined in this study using passive microwave satellite data from the Special Sensor Microwave Imagers (SSM/I) on board Defense Meteorological Satellite Program (DMSP) satellites. For the period 1992–1998, both snow-cover extent and snow depth (snow mass) were investigated during the winter months (May–August) in Argentina and Chile. Most of the seasonal snow in South America is in the Patagonia region of Argentina. Since winter temperatures in this region are often above freezing, the coldest winter month was the one with both the most extensive snow cover and greatest snow depth.

INTRODUCTION

In the Northern Hemisphere, the land masses are situated much closer to the poles than they are in the Southern Hemisphere. The land not only acts as a source area for cold air, but because of its lower thermal inertia compared to water, it does not modify the cold temperatures nearly as much as does water, even cold Antarctic waters. Thus, in the middle latitudes temperatures during the winter months are much cooler in the Northern Hemisphere than in the Southern Hemisphere, and snowfall occurs more frequently. Associated with this is the fact that high-pressure systems or anticyclones occur less often in the Southern Hemisphere than in the Northern Hemisphere. Because there is less land in the middle latitudes of the Southern Hemisphere, the southern westerlies are stronger than their northern counterpart, and large nearly stationary “high” systems such as the “Siberian High” are less frequently established. These large “highs” are important in refrigerating surface air and influencing the strength and tracks of storm systems (Chang et al., 1990). Despite these factors, which act to inhibit snowfall, seasonal snow does occur in the middle latitudes of the Southern Hemisphere and occasionally even in the sub-tropics at elevations below 1,000 m. At elevations above roughly 5000 m, snow can occur even at the Equator.

Using data from the Special Sensor Microwave Imagers (SSMI) on board Defense Meteorological Satellite Program (DMSP) satellites, snow extent and snow depth (snow mass) have been calculated for the period from 1992–1998 in the middle latitudes of the Southern Hemisphere. It should be noted that in mid-winter approximately 99% of the snow cover in the Southern Hemisphere is confined to Antarctica. The data record shows that South America is the only continent in the Southern Hemisphere

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(other than Antarctica) where an extensive, non-mountainous, winter snow cover may occur. Therefore, the emphasis in this study is on South America. The objectives are to map the seasonal snow cover during the cold months of the year using passive microwave satellite data and to generate a snow record comparable to the record for North America and Eurasia. The mapping of permanent snow and ice fields in the higher elevations of the Andes Mountains was not an objective of this study.

Although a considerable amount of effort has been devoted to developing and refining passive microwave snow algorithms for North America and Eurasia (for example, Chang et al., 1987; Goodison et al., 1993; Pulliainen et al., 1993; Grody and Basist, 1996; Foster et al., 1997; and Armstrong and Brodzik, 1999), very little work has been expended for algorithm development of seasonal snowfields in the Southern Hemisphere. Algorithm adjustments will likely need to be made from continent to continent and even from region to region, because differences in land cover and snow crystal size alter the microwave response.

STUDY AREA

Figure 1 is a map of South America showing the location of the Patagonia region of Argentina and the Tierra del Fuego region of Argentina and Chile. In southern Argentina, snow may accumulate as early as May and as late as October. Each winter, snow is a regular feature south of about 45° S. Lat., and in the snowiest years, over 1 million km² of snow has been measured (Dewey and Heim, 1983). A single storm may cover the ground with several hundred thousand km² of snow. Snow can fall at locations much farther north than expected, and it can even lie on the ground for a few days as far north as 27° S. Lat. Snow here is usually confined to elevations greater than 1000 m above sea level, where as much as 30 cm of snow has been observed in southern Brazil (Prohaska, 1976). In July 2000, freezing temperatures and snowfall in southern Brazil and Paraguay damaged coffee crops.

Although the Andes in southern Chile and Argentina can be snow covered throughout the year (Williams and Ferrigno, 1998), again, we are mainly interested in seasonal snow—snow that melts during the spring or summer season. Figures 2 and 3 show plots of July 1994 temperature versus snow cover for the cities of Lago Argentino and Rio Gallegos, respectively (Fig. 1). For Rio Gallegos, snow covered the ground from the 17th onward, and according to meteorological data for this station a coastal storm deposited approximately 60 cm (2 ft) of snow on July 26, 1994!

Typically, snow cover in southern South America results from disturbances embedded in the westerly air streams. East winds and heavy precipitation during the winter in southern South America are caused by quasi-stationary high pressure systems at high latitudes over the western South Atlantic Ocean (Kidson, 1988). These anticyclones block the normally zonal airflow in such a way that normal sea level cyclonic systems are steered around the "high" toward Patagonia (the Argentinian states of Rio Negro, Chubut, Santa Cruz, and Tierra del Fuego). In southeastern Brazil, snow can fall when incursions of polar air from the south push northward, coincident with a weakening of the normally dominant subtropical high-pressure belt.

Although snow cover may be significant in South America in terms of its effects on weather, especially temperature and agriculture, it is variable from year to year. This is to be expected when, typically, accumulations are rather shallow. According

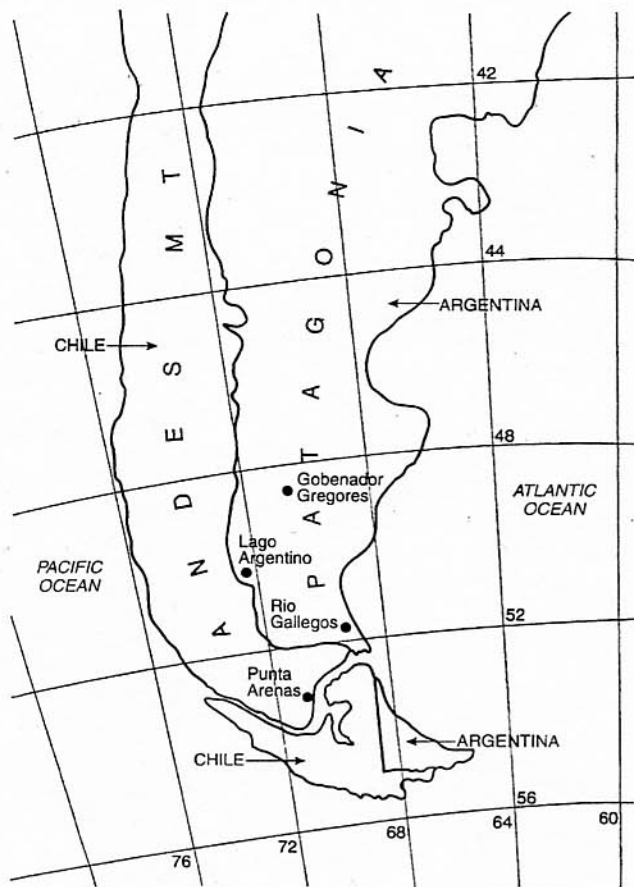


Fig. 1. Map of Patagonia.

to Dewey and Heim (1983), over a seven-year period from 1974 to 1980, snow cover reached a maximum extent of about 1×10^6 million km^2 in 1980, but in 1979, the maximum extent was only about 70% of this amount. For comparison, during the 1980 snow season, snow covered an area about the size of the country of Bolivia in South America (about the size of the states of Texas and Oklahoma combined in the United States or the states of New South Wales and Victoria combined in Australia).

PASSIVE MICROWAVE DATA

The study years used for this investigation (1992–1998) match the years of coverage for the DMSP 11 and 12 satellites, launched in November 1991 and August 1994, respectively (Steffan and Jezek, 1995; Colton and Poe, 1999). Data were acquired from the SSMI on board the DMSP satellites. While only seven years of data were used, it is worth noting that this period includes one very snowy year and one year with little snow. For this investigation, brightness temperature differences between the 19 GHz and 37 GHz channels were multiplied by a coefficient related to the average grain size (1.60) to derive the thickness of the snow (Chang et al., 1987). The simple algorithm is then

$$SD = 1.6 [(T_{19} - T_{37}) - 5] \text{ cm}, \quad (1)$$

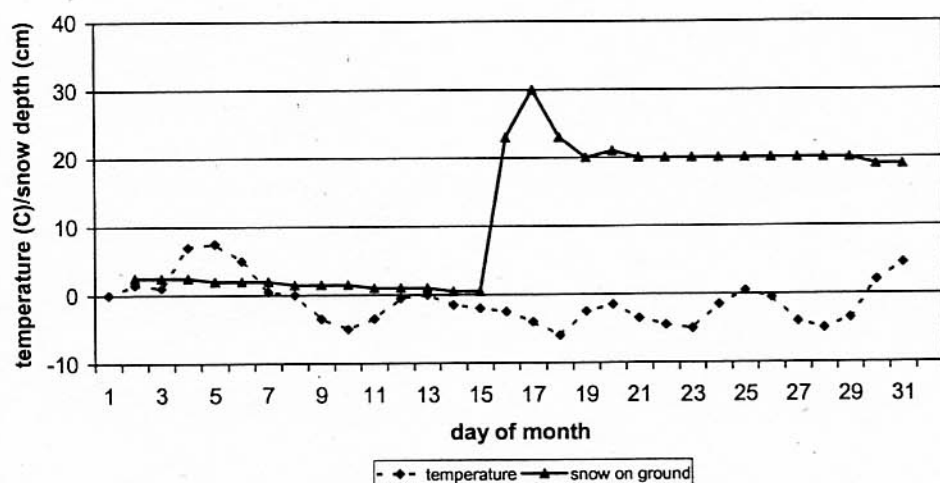


Fig. 2. Average maximum temperature and snow depth on the ground for Lago Argentino, July 1994.

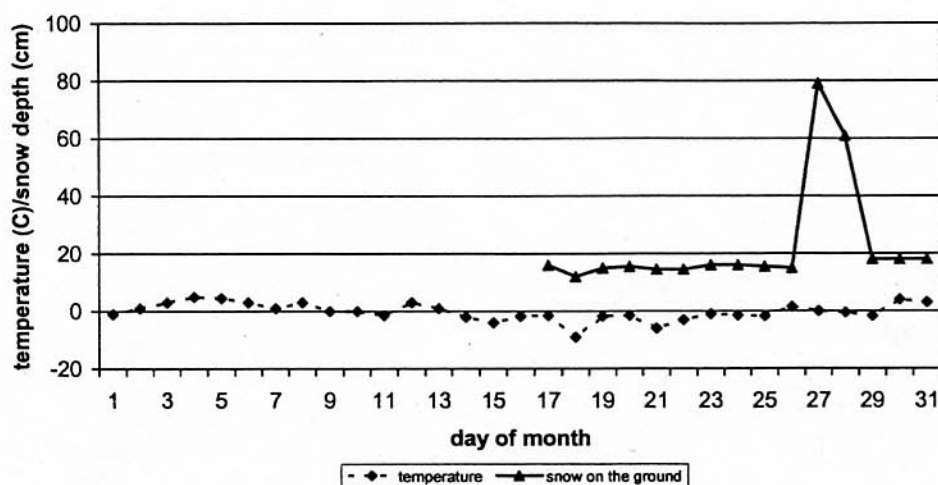


Fig. 3. Average maximum temperature and snow depth on the ground for Rio Gallegos, July 1994.

where SD is snow depth in cm and T_{19} and T_{37} are the brightness temperatures at 19 GHz and 37 GHz horizontal polarizations, respectively.

To derive snow water equivalent, the above algorithm can be multiplied by 3.0—the average density of mid-winter, mid-latitude snowpacks is approximately 300 kg/m³. This is expressed as follows:

$$\text{SWE} = 4.8 [(T_{19} - T_{37}) - 5] \text{ mm}, \quad (2)$$

where SWE is snow water equivalent in mm. If the 19 GHz channel is less than the 37 GHz channel, then the SWE is defined to be zero.

Using data from a study by Van der Veen and Jezek (1993), it was found that a -5 K offset exists between Scanning Multichannel Microwave Radiometer (SMMR)

data and SSMI observations over Antarctica. The above equations include this offset. Improved snow maps resulted when the offset was used. Both the SMMR and SSMI algorithms are based on theoretical calculations using SMMR data. If the SSMI algorithm was based only on calculations using SSMI data, then it would not include the -5 K offset (Armstrong and Brodzik, 2001). While calibrations of SSMI have been found to be somewhat more stable, it is difficult to prove that the accuracy of the SSMI is better than the SMMR.

The nominal resolution for the 19 GHz (actually 19.35 GHz) channel is 69×43 km² and for the 37 GHz channel it is 37×28 km² (Naval Research Laboratory, 1987). Equal Area SSMI Earth Grid (EASE-grid) Southern Hemisphere projections (at a 25 km \times 25 km pixel scale) used in this study were provided by the National Snow and Ice Data Center. The brightness temperature contribution for water vapor is nearly the same at both the 19 GHz and 37 GHz frequencies, and if the clouds contain ice crystals, as they do during the winter months, the difference of the 19 and 37 GHz frequencies will have no effect on the atmosphere, and thus atmospheric corrections are not necessary.

Landsat, which has a 16-day repeat period, or even the Moderate Resolution Spectroradiometer (MODIS) on board the Terra satellite, available every two days at the latitude of southern South America, can be rendered nearly useless by the persistent clouds that often cover Patagonia. Even daily NOAA/Advanced Very High Resolution Radiometer (AVHRR) visible data may not obtain cloud-free imagery over Patagonia for periods of a week or longer. Figure 4 shows snow cover in Patagonia from an AVHRR image—one of only a few relatively cloud free AVHRR images available during July 1995.

Passive microwave remote sensing, therefore, is particularly advantageous in this kind of environment, not only because clouds and darkness do not preclude snow detection, but also because Patagonia has few forests. The emission from trees can confound the scattering signal of snowpacks, and thus if forests are present, adjustments would need to be made to the retrieval algorithms in order to account for the forest emission and resulting increase in brightness temperature.

Disadvantages of using passive microwave radiometry in Patagonia are related to the continental shape of southern South America and the general shallowness of the snow in this region. Shallow snow, less than about 3 cm in thickness, is often transparent to microwave radiation, and therefore no snow may be indicated when employing an algorithm when, in fact, a thin veneer of snow is present. Because the southern part of South America tapers to a point, a number of SSMI pixels at the tip include water from the Atlantic and Pacific oceans. Pixels having more than about 20% water (surface water, such as lakes or bays) render snow retrieval algorithms useless because the very low brightness temperatures characteristic of open water in the microwave portion of the spectrum are emission based and not scattering based.

Meltwater in the snowpack can actually raise the microwave brightness temperature, since water droplets emit rather than scatter microwave radiation. In order to remedy this concern, only nighttime SSMI data were used (approximately 6:00 a.m. overpass time). This helps to ensure, but cannot guarantee, that whatever snow has melted during the day will be refrozen at night.

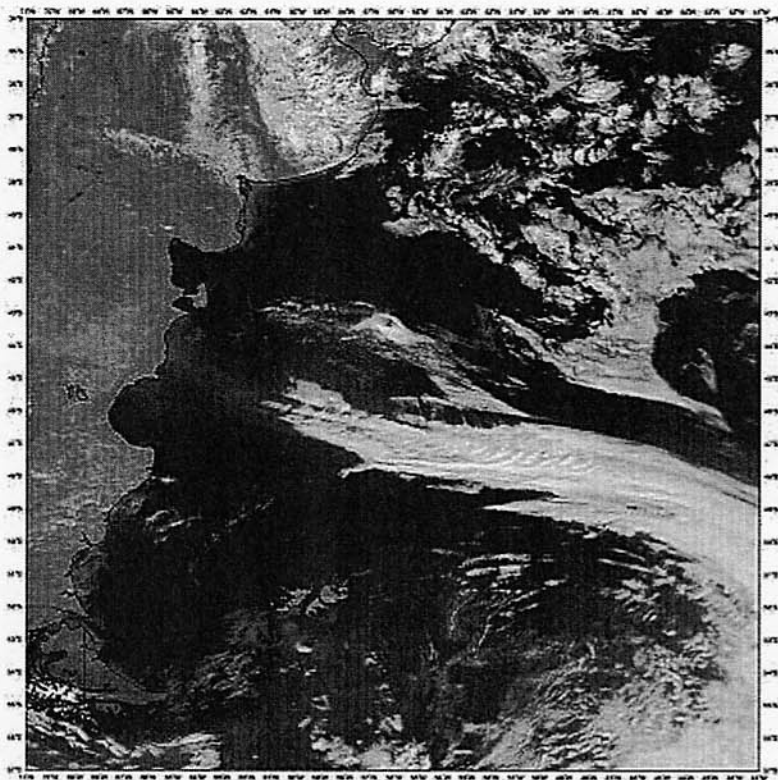


Fig. 4. NOAA AVHRR image of the Patagonia region of South America.

DATA ANALYSIS AND RESULTS

SSMI snow data were acquired from May through August for the years 1992–1998. In order to construct snow maps, 19 GHz and 37 GHz (horizontal) radiances were converted to brightness temperatures. Both average (quasi-average) monthly and monthly maximum maps of snow-cover extent and snow depth (mass) were generated for the 28-month period using equation (1). The average monthly snow depth is given as half of the maximum observed on any day. Thus, if 24 mm of snow was the maximum daily snow for any given pixel during the month, the average snow depth for the month was 12 mm. Of course, this is not a true average, but it gives an indication of the snow depths that can be expected over the course of several weeks. This procedure was used because, while the snow in Patagonia is generally quite shallow and transient, the snow thickness seems to be rather consistent—pixel-to-pixel variance is low. Several different categories are noted on the maps. If the 37 GHz brightness temperature is greater than 250 K or if the 37 GHz and 19 GHz frequency gradient is greater than 10 K, then no snow is assumed. Furthermore, if the snow water equivalent (SWE), from equation (2), is less than 10 mm, the surface is considered snow free. For the microwave maps, our analysis was restricted to land areas south of 25° S. Lat.

In order to assure that the SSMI algorithm is sufficiently sensitive to detect snow on the ground, Figure 5 shows a plot of the monthly average temperature (departure from normal) during the months of May through August for 1992–1998 versus the number of snow-covered SSMI pixels for these same months. The temperatures are

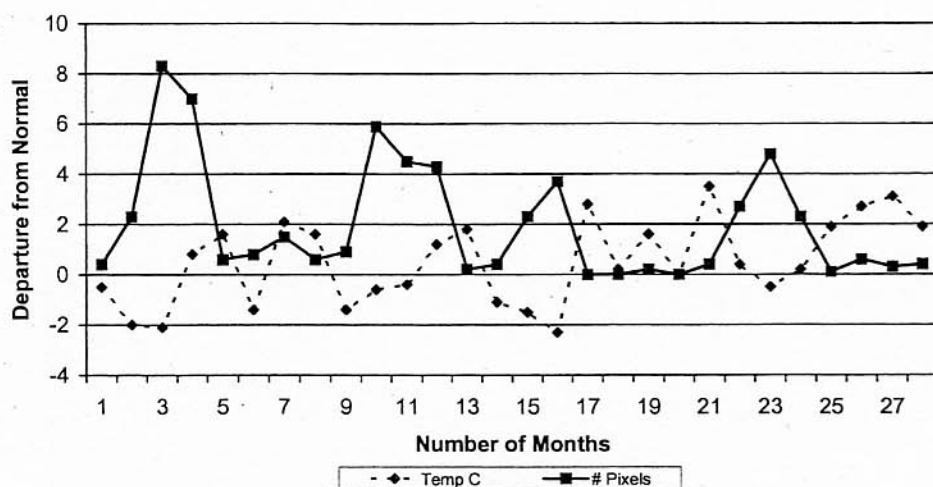


Fig. 5. Average monthly (May–August) air temperature ($^{\circ}\text{C}$) in Patagonia versus snow cover (SSMI pixels).

averaged from four meteorological stations; Gobernator Gregores, Rio Gallegos, and Lago Argentino, Argentina and from Punto Arena, Chile (Fig. 1). It is quite evident that an extensive snow cover (~ 300 SSMI $0.5^{\circ} \times 0.5^{\circ}$ pixels) exists only when the average daily temperatures are colder than normal, and in this region, when the temperatures are above normal, they are almost always above freezing (0°C), quickly melting the snow. This result, and comparison of the estimates with the station data when a snow cover exists, demonstrates that the algorithm is able to discern snow and gives confidence that the snow extent trends are reasonable.

Thus, equation 1 was used to determine the monthly average snow extent and snow mass values from SSMI for the years 1992–1998 (Table 1). The most snow for any year (average and maximum) occurred in 1992, and the year with the least amount of snow was 1996. July 1992 was the month having the greatest snow-cover extent (nearly 0.8 million km^2) and snow mass (approximately 2.58×10^{13} kg).

Figures 6–8 show the seasonal accumulation of snow in Patagonia during the fall and winter of 1992. Table 1 gives the monthly (May–August) snow cover and snow mass for the 1992–1998 period.

ERROR ANALYSIS

A problem with a number of remote sensing approaches in attempting to validate their results is the issue of what to use as a standard of reference or a baseline for comparison. While ground truth data often are assumed to be more accurate and reliable than spaceborne observations, these data are essentially only representative of points in space. Measuring the depth of snow at two points over a km apart could easily result in depths that are different by several cm. Comparing these point data, from meteorological stations, for instance, with satellite pixels that are approximately 25 km on a side in the case of SSMI data, is not especially meaningful. In order to adequately compare and validate spaceborne microwave estimates of snow depth, perhaps 20 or more point measurements across an SSMI pixel are required. In densely populated areas such as the U.S. Midwest, it may be possible to use available data

TABLE 1

Snow Cover and Snow Mass in South America (1992–1998)

Month	Snow extent, 10^5 km^2	Snow mass, 10^{13} kg
1992		
May	4.26	0.85
June	7.08	1.70
July	7.96	2.58
August	6.95	2.36
1993		
May	2.94	0.63
June	5.32	1.24
July	5.70	1.36
August	4.01	0.93
1994		
May	3.87	0.94
June	5.26	1.70
July	6.44	2.01
August	5.21	1.55
1995		
May	1.89	0.39
June	5.60	1.17
July	6.54	1.60
August	6.59	1.80
1996		
May	1.53	0.27
June	3.19	0.62
July	3.07	0.62
August	3.46	0.68
1997		
May	2.17	0.42
June	5.20	1.34
July	7.34	2.12
August	5.67	1.49
1998		
May	1.99	0.43
June	2.43	0.56
July	3.45	0.76
August	3.55	0.82
28-month average	4.59	1.18

from meteorological stations and or local observers to validate the satellite-derived snow depths. However, in remote areas, these point measurements are almost always lacking.

A field program (NASA Cold Lands Mission) scheduled for the winter of 2002 and 2003 in north-central Colorado will help address this concern. The objective is to measure intensely snow depth and snow water equivalent on the ground, and to estimate these same parameters from the air, using airborne microwave sensors, and from space, using SSMI, Advanced Microwave Scanning Radiometer (AMSR), and MODIS data. This will be done for two 6-day periods in both 2002 and 2003. With this sort of dedicated mission to investigate spatial and temporal variations in snow depth, it is hoped that validation efforts will be more realistic in areas where little ground data is available and that error estimates can be made with greater confidence.

DISCUSSION

Normally, in May, the seasonal snow cover in South America is confined to the higher elevations inland as opposed to coastal areas (Fig. 6). Snow cover may be absent in the higher latitudes near sea level, but farther north, more equatorward, in the highland areas of Bolivia, for example, snow may be extensive. As fall progresses into winter, lowland coastal areas also become snow covered (Figures 7–9), even as far north as 45°S. Lat. in interior areas, in some years. Note that because the pixels in the vicinity of Tierra del Fuego (Fig. 1) include sea water, they are not mapped as snow covered, even though they are, in fact, likely to be at least partially snow covered. Although the snow depths are generally less than about 10 cm across most of Patagonia in mid-winter, coastal storms can produce significant snowfalls. In the coastal city of Rio Gallegos (51° S. Lat.), for example, approximately 50 cm of snow fell during a storm in July 1994 (Fig. 2).

Since the snow cover in Patagonia is generally quite shallow, the month having the maximum snow coverage can vary from one year to the next. With few exceptions, however, the coldest month is the month with the greatest snow cover extent. Consequently, July is the month that usually has the greatest snow cover, but in some years August has the most snow. This is the case in North America and Eurasia as well; the greatest snow cover extent occurs during the coldest month (January) or the second coldest month (February).

With respect to snow volume, in the Northern Hemisphere, because the snow accumulates throughout the winter months at the higher latitudes and at highest elevations, the greatest snow volume typically occurs in February or March. In South America, the snowpack is deepest in July and August. By September, much of the snow in the higher latitudes is already melting. In many years, a storm will deposit a layer of snow that melts before another storm arrives. So the month with the deepest snowpack is almost always the month with the greatest snow extent—the coldest month.

On occasion, the snow volume and mass may be greater in a month when the snow extent is less than a month having a greater area of snow cover. In May 1995, for example, only 77 SSMI pixels were snow covered, and the average snow depth per SSMI pixel was approximately 6.3 cm, whereas in June of that year, 246 pixels were snow covered, but the average snow depth per SSMI pixel was slightly less.

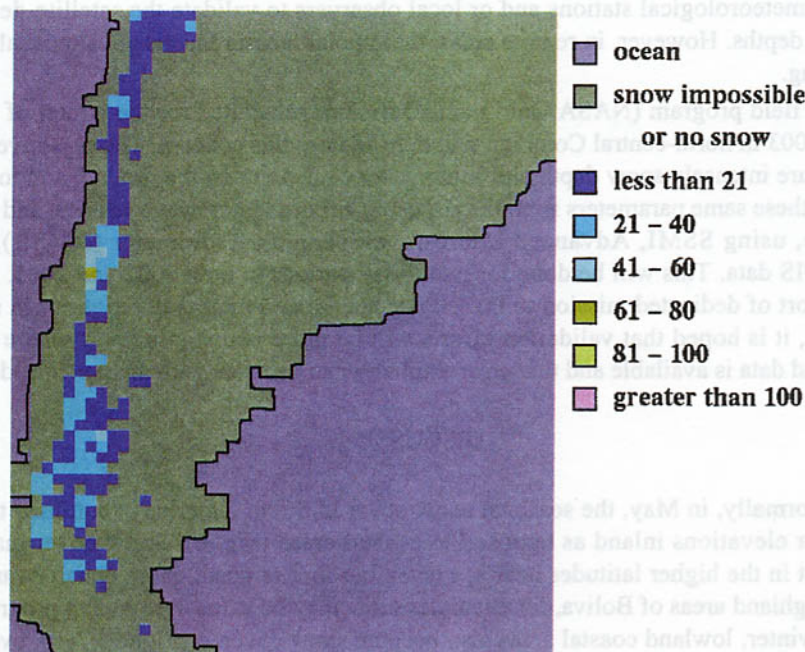


Fig. 6. SSM/I snow cover during May 1992.

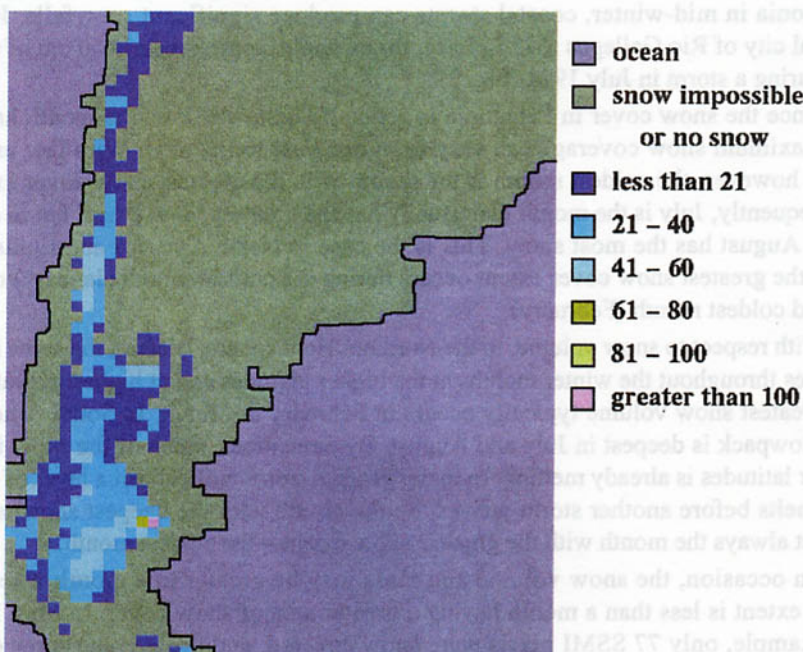


Fig. 7. SSM/I snow cover during June 1992.

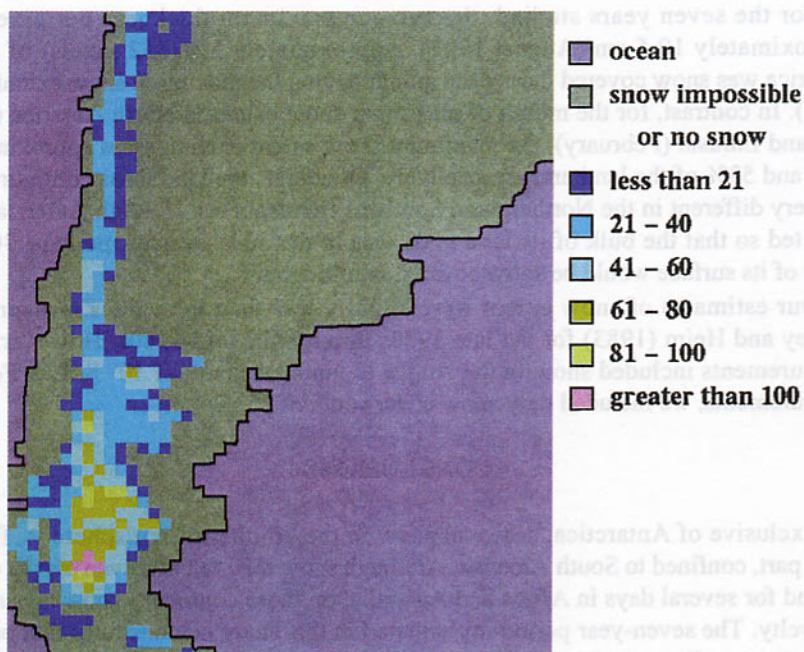


Fig. 8. SSMI snow cover during July 1992.

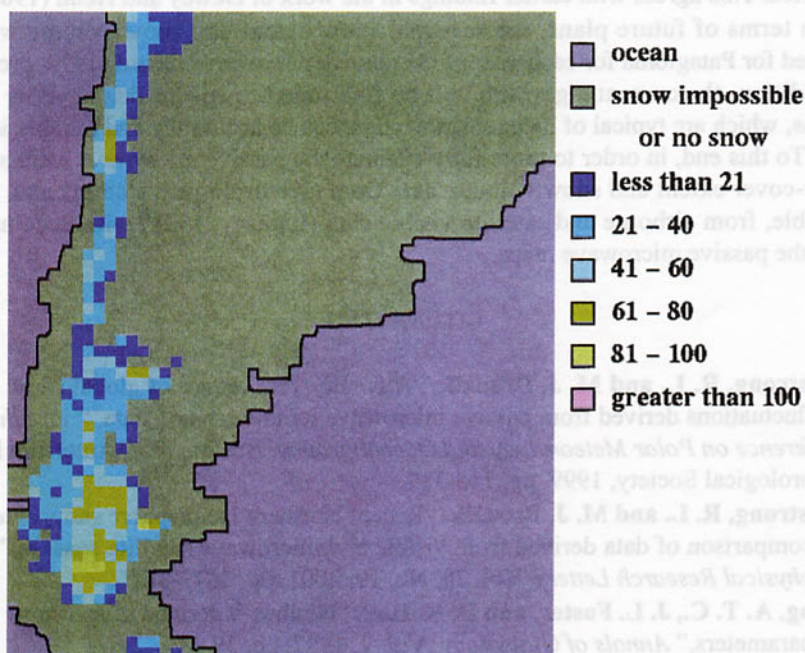


Fig. 9. SSMI snow cover during August 1992.

For the seven years studied, the average maximum thickness per pixel was approximately 10.5 cm (August 1992). Approximately 5% (352 pixels) of South America was snow covered during the month having the maximum snow extent (July 1992). In contrast, for the month of maximum snow extent in North America (January) and Eurasia (February), the maximum snow extent encompasses approximately 62% and 53% of the land area, respectively. Of course, the land mass configurations are very different in the Northern and Southern Hemispheres. If South America were inverted so that the bulk of its land mass was in the mid latitudes, perhaps 30% or more of its surface would be snow covered in mid-winter.

Our estimates of snow extent were slightly less than the values measured by Dewey and Heim (1983) for the late 1970s through the mid-1980s. However, their measurements included snow in the Andes Mountains, south of 10° S. Lat. For our measurements, we included only snow cover south of 25° S. Lat.

CONCLUSIONS

Exclusive of Antarctica, seasonal snow in the Southern Hemisphere is, for the most part, confined to South America. Although snow may fall and even persist on the ground for several days in Africa and Australia, on those continents snow is basically a novelty. The seven-year period investigated in this study demonstrates that passive microwave radiometry is especially useful in estimating the snow-cover extent and snow mass in areas where clouds are a nearly constant problem and where the snow is usually ephemeral. The passive microwave observations show that sharp year-to-year differences exist in the seasonal snow extent over the Patagonia region of South America. This agrees with earlier findings in the work of Dewey and Heim (1983).

In terms of future plans, the seasonal snow extent and snow volume will be derived for Patagonia for each year of the passive microwave record (1979–present). In addition, the current algorithm will be fine-tuned to ensure that shallow snow depths, which are typical of Patagonian winters, can be accurately and reliably identified. To this end, in order to more fully evaluate the passive microwave estimates of snow-cover extent and snow volume, data from meteorological stations and, when possible, from airborne and satellite visible data (Ramsay, 1998) will be compared with the passive microwave maps.

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